Research on the Prediction of Waterlogging Points and Flood Prevention in Urban Pipe Network based on SWMM Modeling

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Abstract. Global climate change, increasing extreme precipitation, and the growing problem of urban flooding. Establishing a model that can quickly and accurately simulate the prediction of urban pipeline waterlogging points is a problem that needs to be solved urgently. In this paper, based on the Storm Water Management Model(SWMM), the distribution of pipeline network node ponding points in Baolong Street, Longgang District, Shenzhen City, Guangdong Province, is simulated under different recurrence periods of heavy rainfall, and the pipeline node ponding is used to predict the ponding points in the study area. The results show that the model can accurately predict the historical waterlogging points in the area and realize the simulation of urban flooding waterlogging. Deficiencies in the stormwater carrying capacity of the pipes in the study area were also identified. The model is different from other complex two-dimensional models, simplifies the complexity of the model, reduces the amount of computation can quickly and accurately simulate the prediction of urban waterlogging points. It has an important role in early warning and forecasting for urban flood prevention and control.

Keywords: Urban flooding; SWMM model; waterlogging point prediction; drainage system improvement.

1. Introduction

With global climate change, extreme weather events occur frequently, seriously affecting people's production and life. Globally, 7348 self-heating disasters occurred in the two decades of 2000-2019, causing about 1.2 million deaths, of which flooding accounted for 44% is the first of all types of natural disasters [1]. With the emission of greenhouse gases and global warming, flood disasters will seriously affect people's lives in the future [2]. Meanwhile in the context of climate change compounded flood disasters pose a serious threat to coastal cities.

The urbanization rate and population density of economic activities affect the intensity and frequency of flooding, in the high urbanization rate, high population density, frequent economic activities, which also makes the city “rain island effect” highlighted [3,4]. Therefore, the risk of flooding in the PRD region is high, and the damage caused will be huge. This is not conducive to social stability and economic development. It is a major resistance to social stability and economic development. The relevant report pointed out that in 2022 alone, a total of 33,852,600 people were affected by flooding, accounting for 30.87% of the total dead and missing population of natural disasters in that year, and the direct economic losses amounted to 128,899,000,000 Yuan, accounting for 54.01% of the total direct economic losses of natural disasters in that year [5].

Therefore, in the Pearl River Delta (PRD) in South China, it is of great significance to analyze the waterlogging points of the pipe network for the drainage of flooding in the city. A lot of research has been carried out at home and abroad, with the development of science and technology and computers, we use more computerized hydrological models to simulate the waterlogging and drainage process of pipe networks. Qiu Zhuang and others based on the Storm Water Management Model (SWMM) of the old neighborhoods of the waterlogging point analysis, analysis of the traditional stormwater design of the community in the design of rainfall and extreme weather conditions in the drainage capacity [6]. Xiao Tong and others based on the SWMM model and the Newflood model of the urban surface water hydrology and hydrodynamics of the coupled model, simulation of the different recurrence periods of the design of the rainfall scenario under the change of the flooding of waterlogging in the study area The response characteristics of urban flooding to different rainfall intensities were analyzed [7]. Shen Di et al used the SWMM one-dimensional model as the research basis to establish an inundation model for the historical inundation sites in Haizhu District, Guangzhou City, which realized the simulation and analysis of the depth of urban inundation [8]. The model simplifies the traditional complex surface two-dimensional model and transforms the impact of heavy rainfall on the flooded waterlogged points into the relationship between heavy rainfall and the pipe network, which greatly reduces the calculation amount.

In this paper, the SWMM model is used to predict and simulate the urban pipe network ponding points under different design rainstorms in Baolong Street, Longgang District, and Shenzhen City, Guangdong Province. The problems existing on the official website of the neighborhood where it is located are proposed. And provide some improvement measures in order to provide a reference for urban flood prevention in this intercept.

2. General situation

2.1. Basic information on the study area

2.1.1. Location of the study area

The study area is located in Baolong Street, Longgang District, Shenzhen City, Guangdong Province, which lies in the eastern part of Longgang District, at the junction of Longgang and Pingshan Districts, bordering Longcheng Street and Yanshan Street in the west, adjoining Pingshan District in the east and south, and connecting with Pingdi Street and Longgang Street in the north (Fig.1). The study area covers about 5.36 square kilometers.

Fig 1. Location map of the study area.

2.1.2. climatic conditions

The study area is located south of the Tropic of Cancer and has a warm and humid maritime monsoon climate in the southern subtropics, with warm and temperate weather throughout the year, long but not hot summers, and abundant rainfall. Since there is no rainfall station in the area, according to the measured rainfall data of the neighboring Qinglin Trail rainfall station at the upper reaches of the Longxi River for 39 years from 1963 to 2005, the maximum annual rainfall is 2476 mm (1986), the minimum annual rainfall is 979 mm (1963), the maximum is 2.5 times of the minimum annual rainfall, and the average rainfall for many years is 2099.89 mm. The rainfall during the year mainly concentrates on the months of April to September, during which the rainfall accounts for about 1.4% of the total. The annual rainfall was mainly concentrated in April to September, during which the rainfall accounted for about 85% of the whole year.

The annual rainfall is mainly concentrated in April to September, which accounts for about 85% of the yearly rainfall. The rainfall in the study area varies greatly from year to year, and the statistics of rainfall in Shenzhen Reservoir for the period of 1960-2002 show an increasing trend. The 43-year average rainfall at the Shenzhen Reservoir station was 1975.16 mm, with the maximum annual rainfall of 2747 mm in 2001, and the minimum annual rainfall of 849.7 mm in 1963, the maximum annual rainfall being 2.3 times the minimum annual rainfall. The average annual rainfall in the rainy season is 1689.9 mm, accounting for 85.8% of the average annual rainfall. The average annual rainfall in the early season is 285.4mm, accounting for 14.2% of the average annual rainfall.

2.1.3. Status of the current drainage system

According to the information of Shenzhen Longgang District Environmental Water Bureau drainage network, and combined with the image map, the study area has a high degree of completion, and municipal stormwater drains have been laid along the road, the length of the pipe network is about 26.42 kilometers, and the range of pipe diameters is d600 ~ A6 × 3.5 (Fig.2).

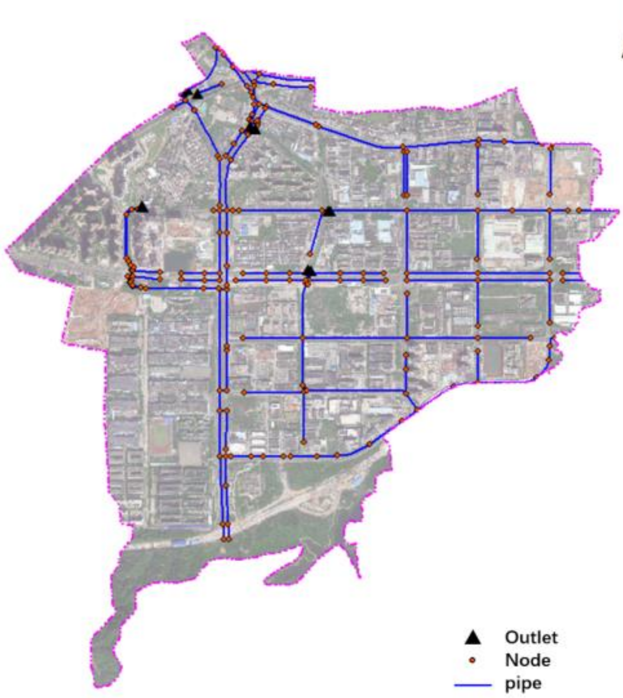

Fig 2. Pipe network map of the study area.

2.1.4. Historical flooding conditions

According to the information of historical flooding points of Longgang District Environmental Water Bureau of Shenzhen City, the survey of historical flooding is based on the database of flood-prone areas and important waterlogging points in Longgang District with many years of records, with emphasis on reference to the waterlogging points formed by several heavy rainfalls in recent years, and the waterlogging points are categorized and analyzed according to the degree of waterlogging, the location of the block, and the causes of waterlogging. The terrain is lower than the design flood tide level of one in 50 years of natural low-lying land or urban development of local man-made depressions, drainage facilities are not perfect, resulting in a relatively concentrated area of flooding, the depth of water is greater than or equal to 30 centimeters, the time of accumulation of water is greater than or equal to 30 minutes, the catchment area of greater than or equal to 1,000 square meters. Then this type of area is flood prone.

There are two flooding points in the study area, which are at the Jaguar Field section of Bao Ho Road and Bixin Road. Among them, the maximum flooding depth at the Jaguar Field section of Baohe Road is 0.4 meters and the maximum duration is 0.5 hours, while the maximum flooding depth at Bixin Road is 0.3 meters and the maximum duration is 0.4 hours (Fig.3).

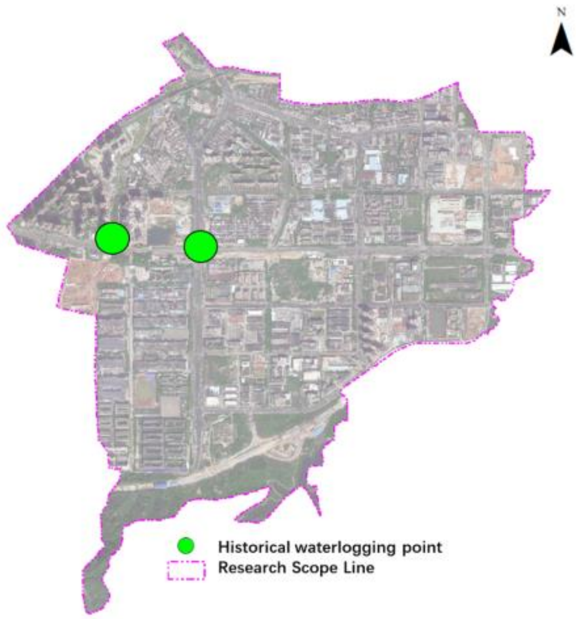

Fig 3. Schematic diagram of historical flooding sites in the study area.

2.2. Overview of the SWMM model

SWMM is used to simulate dynamic precipitation runoff from urban storms. It has good application in urban stormwater pipe design, stormwater pollution prevention, and single or long time continuous simulation of runoff water quantity and quality. Therefore, the SWMM model is used in this study to simulate the flooding and waterlogging situation.

2.2.1. Model Features

The SWMM model can simulate urban hydrological processes such as rainfall, evaporation, snowmelt, depression retention, infiltration, and groundwater interaction, and reflect spatial variability by delineating sub-catchment areas. At the same time, the model can simulate the flow of rainfall runoff and external water flows in pipes and water storage facilities, and supports customized control rules to adjust parameters such as pumps and overflow weirs.

2.2.2. Modeling Principles and Calculations

SWMM is a distributed hydrologic model that follows the laws of conservation of mass, momentum, and heat in the simulation process. The simulation process of urban storm runoff and water quality is accomplished through the processes of surface flow production, infiltration, groundwater, snowmelt, and surface ponding in SWMM.

(1) Surface runoff

In the SWMM model, each sub catchment is treated as a nonlinear reservoir, with inflow terms of precipitation and outflow from upstream subcatchments: outflow terms of infiltration, evapotranspiration, and surface-produced flow. The maximum depression storage volume is the volume of the pool, and the depression storage volume includes the amount of water that ponds, wets the surface, and is retained. Surface runoff occurs when the depth of the pool exceeds the depth of the depression storage volume, and the magnitude can be calculated by Manning's formula:

$$Q = W\frac{1.49}{n}(d - d_p)^{\frac{5}{3}}S^{\frac{1}{2}} \tag{1}$$

W: inherent width of the watershed, S: slope, d: water depth in the sub-catchment area, dp: maximum storage water depth in the sub-catchment area, N: Manning's roughness coefficient.

(2) Infiltrate

Infiltration is the process of movement of rainwater that falls to the ground and seeps down into the soil. SWMM provides three options to simulate the process of rainfall infiltration.

The method is based on empirical observations showing that infiltration decreases exponentially, from an initial maximum rate to a minimum rate, throughout the long-term rainfall time course [9]. The input parameters required for this method include the maximum and minimum infiltration rates, a decay coefficient that describes how the rate decreases with time, and the time it takes for a fully saturated soil to be completely drained.

The Green-Ampt infiltration model is more commonly used in describing vertical infiltration processes. The model assumes that different depths within the soil layer have the same water content before infiltration [10]. During infiltration, there is a distinct wetting peak drop that divides the soil into two parts: saturated and unsaturated regions. It is assumed that the ponding of water on the ground surface is negligible. The wetting peak drop equation is determined based on Darcy's law. The model involves the following parameters: initial moisture content of the soil, soil hydraulic conductivity, and the suction head of the wetting front.

The curve approach assumes that the infiltration capacity of the soil is derived from the number of changing curves in the soil table and that the infiltration capacity decreases as a function of cumulative rainfall and residual capacity. Input parameters include the number of curves and the time required for fully saturated soil to drain.

(3) Confluence calculation

There are three methods in SWMM: steady wave, kinematic wave, and power wave to compute constant and non-constant flow in a drainage network [11]. The power wave method uses the St. Venant system of equations to solve the continuity and momentum equations in pipes and drains as well as the conservation of mass at the nodes. The power wave method is capable of calculating pressurized flow in closed pipes at full capacity, and water can flow beyond the full capacity flow of the pipe network. When the water depth at a node exceeds the depth of the node, the excess water is either lost from the system or stored at the previous node. The conduit load is reduced and then fed into the drainage system.

Because the power wave method solves the problems of water depth at nodes and the movement of pressurized water in conduits, it is able to simulate the change in storage volume, backwater, inlet and outlet losses, backflow, and pressurized water flow in the network. The power wave method can be applied to annular closed pipe networks, as well as to situations with multiple steering gears.

3. Analysis of model results

This model simulation time and time step settings, simulation options at the end of the analysis time is 6h, and the report time step is 5 min. model simulation using power wave.

3.1. Rainfall data generation

According to the “Shenzhen Stormwater Intensity Formula and Chart for Checking and Calculating (2015 Edition)”, the formula for stormwater intensity in Shenzhen is shown below:

$$q = \frac{1450.239(1+0.594\lg P)}{(t+11.13)^{0.555}} \quad (2)$$

q - Storm intensity (L/s-ha); P - return period (a); t - rainfall duration (min)

The latest version of the Shenzhen Storm Intensity Equation was utilized to derive the design rainfall under different recurrence periods to generate the 2-hour design rainfall for the 2-, 5- and 10-year recurrence periods over time (Table 1).

Table 1. Extrapolation of design rainfall.

Recurrence period(year)	Design rainfall(mm)
2	75.74
5	98.83
10	112.75

3.2. Assessment and analysis of waterlogged sites

3.3.1. 2-year rainfall results

Under the 1-in-2-year rainfall scenario, which was 75.74mm, a total of 13 nodes produced over 1,000 cubic meters of flooding. 11,220 m3 of flooding was generated near Bixin Road (node XZnode3810), where the pipe network was small and could not meet the drainage demand; 10,124 m3 of flooding was generated near the Jeguktian section of Baohe Road (nodes XZnode3814 and XZnode1004), where there was a large amount of passenger water, which needed to take on the rainwater on the south side, and where the pipe diameter was too small to drain the rainwater in a timely manner. The flood prone points in this simulation have a high degree of overlap with the historical flooding points in Fig. 4.

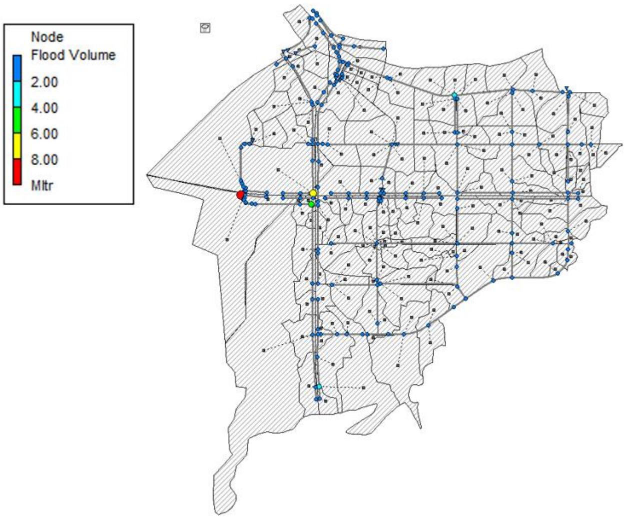

Fig 4. Plan of the 2-year model.

3.3.2. 5-years rainfall results

Under the 1 in 5 year rainfall scenario of 98.83mm, a total of 17 nodes produced flooding conditions exceeding 1,000 cubic meters. In the Bixin Road (XZnode3810 node) near the generation of 15,800 cubic meters of flooding, the place of the pipe network is small, cannot meet the drainage needs; in the Baohe Road Jieguotian road section (XZnode3814, XZnode1004 node) near the generation of 25,333 cubic meters of flooding, the place of the passenger water is larger, need to take over the south side of the rainwater, the diameter of the pipe is small, cannot be in a timely manner to drain the rainwater. In addition the north side and east side also again localized flooding points began to be serious, the important reason is that the drainage pipe network is small (Fig.5).

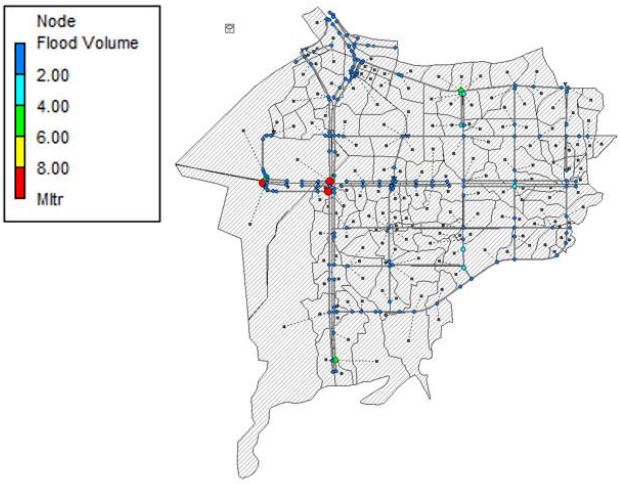

Fig 5. Plan of the 5-year model.

3.3.3. 10-years rainfall results

In the 1 in 10-year rainfall scenario, the rainfall was 112.75mm and a total of 23 nodes produced flooding of more than 1,000 m3. 1 in 10 years is an exceedance rainfall, which is already higher than the standard of the pipe network design, and this scenario further exacerbated the flooding points in the area. In the vicinity of Bixin Road (nodes XZnode3810 and XZnode3812), 27,523 cubic meters of flooding was generated, where the pipe network was small and could not meet the drainage demand; in the vicinity of Jeguktian section of Baohe Road (nodes XZnode3814 and XZnode1004), 330,070 cubic meters of flooding was generated, where the passenger water was large and needed to take on the rainwater on the south side, and the diameter of the pipe was small, unable to discharge rainwater in time (Fig.6).

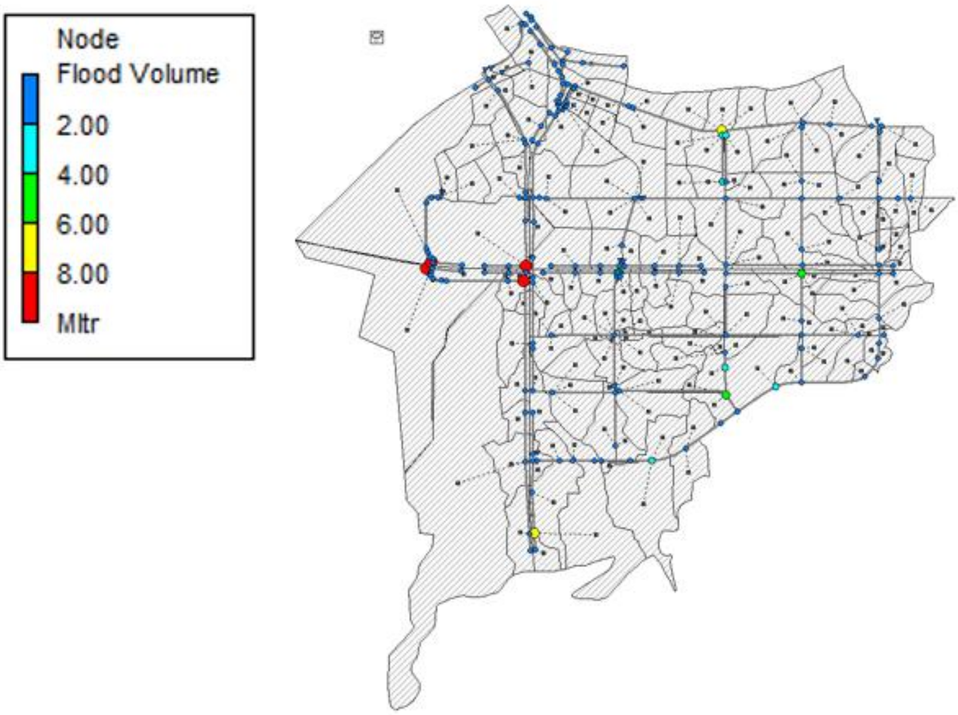

Fig 6. Plan of the 10-year model.

3.3. Assessment Summary and Recommendations for Rehabilitation

Combined with the above results, the assessment is summarized as follows: (1) under the 1 in 2 years return period, the local section node flooding, indicating that the local pipeline cannot meet the drainage demand; (2) as the return period becomes larger, the node inflow becomes larger, the pipeline's ability to carry rainfall gradually decreases; (3) in the event of exceeding the standard rainfall (e.g., the 1 in 10 years), the risk of node flooding becomes higher, and the pipeline overloading operation is particularly obvious.

It is recommended that the existing drainage system be appropriately upgraded and improved to adapt to more intense rainfall events and the impacts of climate change, and to achieve rapid drainage of rainwater; and that green infrastructure, such as sponge cities, be considered, which is in line with the concept of eco-civilization as well as improving the city's flood prevention capacity and reducing the risk of inundation.

4. Conclusion

In this paper, from the perspective of urban flood prevention, the SWMM model was used to predict and simulate the waterlogging points of the urban pipe network under different design rainstorms in Baolong Street, Longgang District, Shenzhen City, Guangdong Province, and the main conclusions are as follows.

(1) The prediction and simulation of waterlogging points on the official website based on the SWMM model has a high degree of overlap with the actual historical flooding, which indicates that the model used is able to simulate urban flooding better.

(2) As the rainfall recurrence period increases, the node inflow volume increases and the capacity of the pipe to carry rainwater gradually decreases. In the case of excessive rainfall (e.g., 1 in 10 years), the risk of nodal flooding increases significantly, and the phenomenon of overloaded pipe operation is particularly obvious.

(3) Pik Sun Road and the Jaguar Field section of Bowrington Road are the major flooding points in the study area. The pipe network near Pik Sun Road is small, while the Jaguar Field section of Bowrington Road is required to carry a large amount of stormwater from the south side, and the pipe diameter is small.

It is recommended that the existing drainage system should be suitably upgraded and improved to cater for more intense rainfall events and climate change impacts. Consideration should also be given to the construction of green infrastructure such as sponge cities to improve the city's flood prevention capacity and reduce the risk of flooding.

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